BLAST RESPONSE OF CONCRETE WALLS WITH STAY-IN-PLACE PVC FORMS

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Wall fragments are responsible for a significant percentage of injuries and fatalities on building occupants during a terrorist attack. The success of polymer research pioneered at Tyndall Air Force Research Lab has lead to research into stay-in-place polymer (polyvinyl chloride- PVC) forms for concrete walls. Research targeting composite behavior of concrete and PVC under blast loads is the focus of this research paper. Laboratory and full-scale explosive test results are summarized to support resistance function calculations for non-reinforced concrete walls with stay-in-place PVC forms.

BACKGROUND AND INTRODUCTION

AFRL ushered in the use of polymers for blast protection beginning in 1998. Engineering technical letters (ETL's) were published in 2002 for retrofitting lightweight structures[1] and non-load bearing masonry walls[2] with polymer coatings to capture and contain secondary wall fragments. Studying concrete forms made from polymers is a logical evolutionary step for researching the advantages of polymers for blast protection. The system chosen for the initial research effort is a PVC form manufactured as a single extrusion. Figure 1 illustrates typical wall construction.
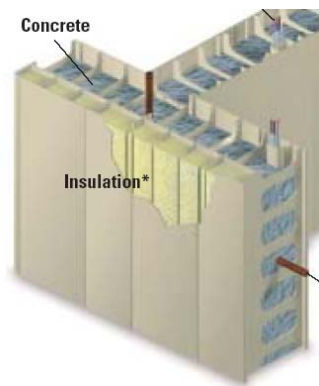

Figure 1: Stay-in-Place PVC Form Wall Construction

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14. ABSTRACT

Wall fragments are responsible for a significant percentage of injuries and fatalities on building occupants during a terrorist attack. The success of polymer research pioneered at Tyndall Air Force Research Lab has lead to research into stay-in-place polymer (polyvinyl chloride-PVC) forms for concrete walls. Research targeting composite behavior of concrete and PVC under blast loads in the focus of this research paper. Laboratory and full-scale explosive test results are summarized to support resistance function calculations for non-reinforced concrete walls with stay-in-place PVC forms.

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Stay-in-place forms, PVC, blast protection, blast response

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The vast majority of concrete walls are reinforced with steel to take the tensile stresses developed during flexural response. Walls constructed with PVC forms are no different, reinforcing steel is sized to take all tensile forces per the applicable engineering design codes. When the focus is on determining blast resistance/protection the research should take full advantage of all components used to construct the wall. The strength of PVC is weak in direct comparison to steel but its contribution in a dynamic energy balance is not insignificant, primarily due to the percent elongation it can withstand prior to tensile rupture. Understanding the composite behavior of a concrete wall constructed with a stay-in-place PVC form is greatly simplified by the absence of reinforcing steel. It is this desire for simplification and clarity of understanding that motivated AFRL to focus initial research on PVC form constructed walls without reinforcing bars. Sections that follow present the results of this research through February, 2005.

TESTING AND EXPERIMENTS

Understanding how a concrete wall constructed with stay-in-place PVC form responds to a blast requires in-depth knowledge of the PVC material strength as well as its composite strength during flexural response. AFRL conducted a full series of coupon tests to achieve the desired material characterization data and developed unique laboratory apparatus and procedures to correlate material strength with composite PVC-concrete flexural behavior.

Material Characterization

Key characteristics for most materials, including PVC, change with strain rate. Published industry standard ASTM test data for the extruded PVC form components are 5,750 psi tensile strength, 2.5% elongation at yield and 27% elongation at break characteristics. These values are determined using quasi-static stroke or specimen pull rates of 2 - 20 inches per minute which correlates to strain rates of 0.025 – 0.25 in./in per second for a Type IV specimen. Depending on wall construction, mass, the type of explosive, charge weight and standoff distance, the blast response for a typical wall generally takes between 15 and 60 milliseconds. To understand the composite blast behavior of PVC form walls requires material data at strain rates which are 1-3 orders of magnitude faster than industry standard data. The AFRL PVC specimen testing matrix is shown in Table 1.

Table 1: PVC Material Characteristic Test Matrix

Source	Specimen	Gage Length	Stroke Rate (in./sec.)	Repetitions
Face PVC	D638 Type IV	1.0"	0.003	3
Face PVC	D638 Type IV	1.0"	0.03	3
Face PVC	D638 Type IV	1.0"	2	3
Face PVC	D638 Type V	0.3"	10	3
Face PVC	D638 Type V	0.3"	100	3
Face PVC	D638 Type V	0.3"	200	3
Face PVC	D638 Type V	0.3"	400	3

The larger Type IV specimens generally give more consistent results for tensile tests and are recommended in ASTM D638 whenever possible. Testing at 2 in./sec and slower was conducted using a typical MTS machine and grips. AFRL is one of the few labs in the U.S. with a high strain rate testing machine capable of a 400 in./sec stroke rate. The smaller Type V specimen produces more reliable results at the faster stroke rates and a maximum applied load of 1,000 pounds. Figure 2 shows a close-up of a test specimen in the high strain rate machine grips designed and fabricated at AFRL and an illustration of the slack adapter that allows the actuator to achieve the desired speed before loading the gripped specimen.

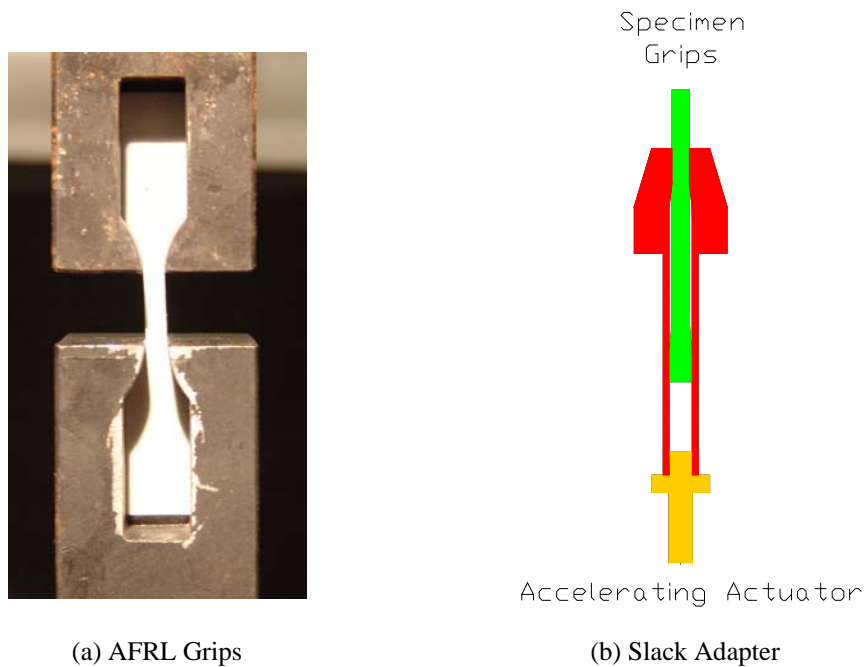(a) AFRL Grips   (b) Slack Adapter

Figure 2: High-Strain Rate Testing Apparatus

Sample charts for engineering stress-elongation data at stroke rates of 2 in./sec and 200 in./sec are shown in Figure 3(a) and 3(b). Raw data for these high stroke/strain rates requires a great deal of evaluation, engineering judgment and cleanup to extract meaningful results. Most of the uncertainty is related to actuator position which is carries over into strain data. The interpreter of high strain rate test results has to account for the following realities during the data mining process.

- Electrical signal output for the force link and linear variable differential transducer (LVDT) measuring actuator position are both impacted by stress waves traveling through the actuator, slack adapter, grips and specimen.
- Tolerances for component fit and mating surfaces inherent to the grip design configuration (thread fit, coupon fit, spacers, etc.).
- Friction between the slack adaptor components (identifying the initial specimen loading point).

AFRL has recently added software that works with high speed video for a vastly improved method to gather strain data correlated to the force data. The PVC data will be repeated at a later date using this method.

The repetition averages for each test from Table 1 are shown in Table 2. Two important characteristics in predicting blast response are maximum strength and maximum elongation. As Table 2 illustrates, strength increases with strain rate while the maximum elongation decreases. Toughness is the area under the stress-strain curve and a good comparison value for combining these two factors. It decays slowly from low to high strain rates. The trends for elongation at maximum strength and modulus seem to indicate that PVC softens at higher strain rates. This information has been factored into the single degree of freedom and finite element models in the Analysis section.
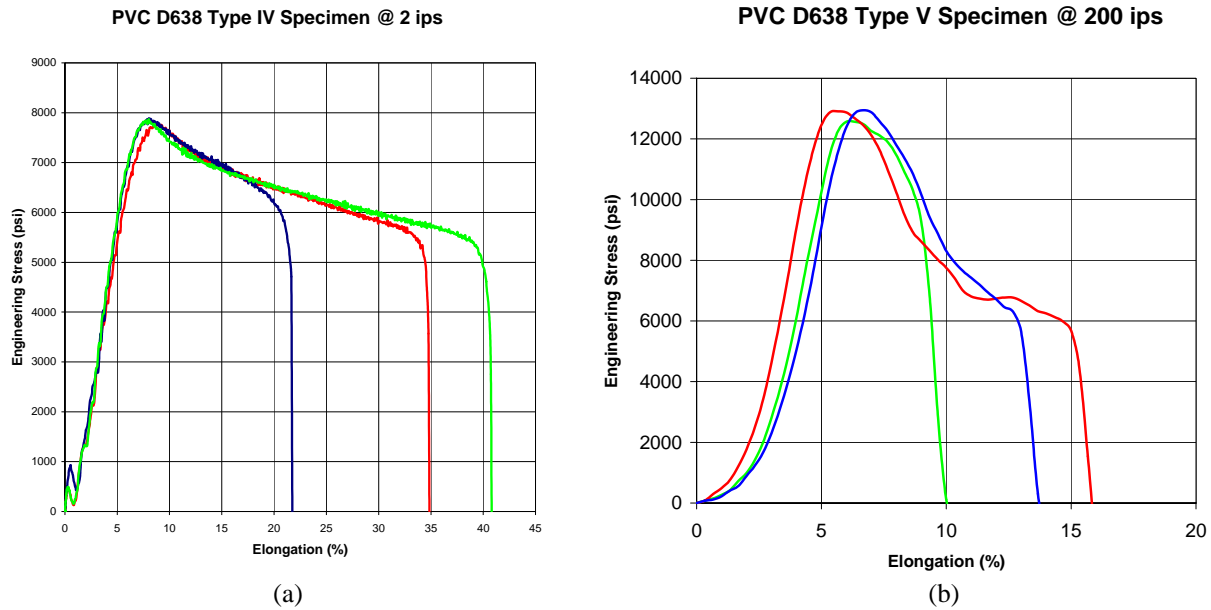
PVC D638 Type IV Specimen @ 2 ips

(a)

PVC D638 Type V Specimen @ 200 ips

(b)

Figure 3: PVC Specimen Strength Curves

Table 2: PVC Material Characteristics

Stroke (in./sec)	Max Strength (psi)	Strength Increase (%)	Elongation @ Max (%)	Max Elongation (%)	10-60 Secant Mod. (psi)	Toughness (psi - in./in.)
0.003	5,880		5.89	48.92	146,198	2,091
0.030	6,488	10.3	6.75	42.09	148,821	1,662
2	7,842	33.4	8.28	37.64	135,483	1,914
10	7,164	21.8	20.83*	43.33*	103,669*	1,765*
100	8,871	50.9	14.00*	19.78*	206,814*	996*
200	12,809	117.8	6.11*	16.33*	281,356*	902*
400	17,250	193.4	11.26*	18.67*	204,129*	1,484*

* These values are heavily influenced by the data mining process

Composite Flexural Behavior

A concrete wall constructed with PVC forms transitions through a series of behaviors as it responds from zero load to complete failure. It is important to understand these behaviors or mechanisms in order to predict success or failure under blast loads using analysis. Behavior prior to concrete cracking is straight forward and reasonably predictable. Once a flexural crack forms and separation progresses as the wall deflects, there are a few questions regarding the interaction between PVC form and concrete. Unique laboratory tests were designed to investigate these interactions.

Wrench Test

The typical quarter point panel testing procedure (ASTM E72) and apparatus were considered inadequate for observing composite flexural behavior and failure. The typical apparatus interferes with the sample at panel deflections less than the point of complete failure and the hydraulics required to load the sample from zero to complete failure in one second were impractical. AFRL designed a method, referred to as the wrench test, for a standard MTS machine which allowed the breaking of samples in flexure using a one second loading cycle. The wrench test is illustrated in Fig. 4 and provided knowledge of the cracking and failure points/mechanisms and there

sequence as the response transitions from uncracked to cracked to maximum strength to rupture. The recorded load data was also used to validate moment capacities included in the single degree of freedom models.
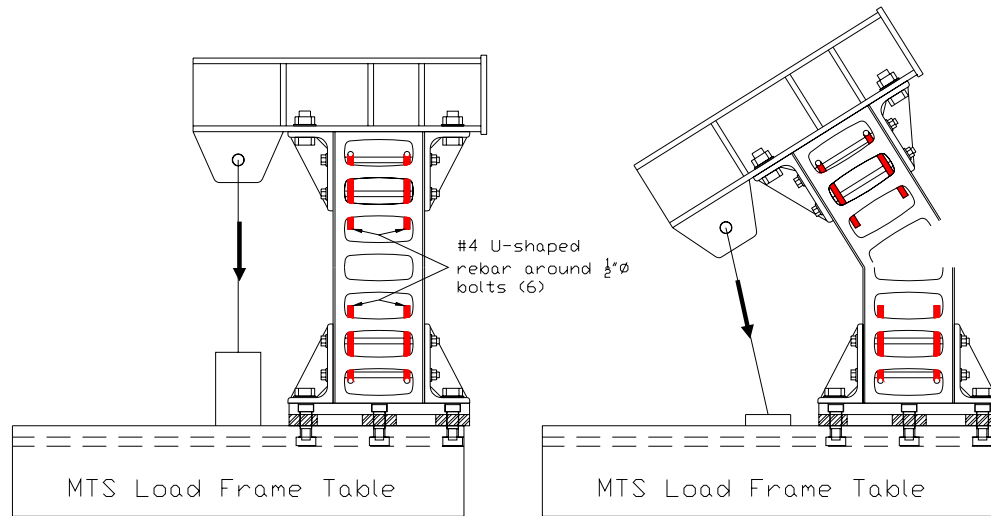

Figure 4: AFRL Flexure Wrench Test

Rod Tension Test

Two local failure modes were postulated during crack separation as the wall deflects: (1) that the webs may tear vertically in flexural shear (VQ/IT) or (2) they may tear horizontally from the inside out. AFRL designed another unique method for a standard MTS machine referred to as the rod tension test to investigate these possibilities. The single and double rod tension tests are illustrated Fig. 5. Load data was recorded during each test.
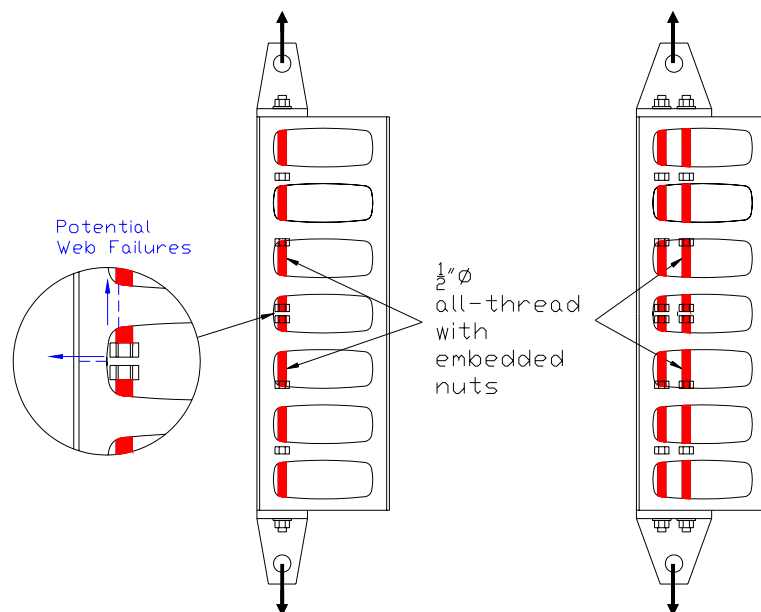

Figure 5: AFRL Single & Double Rod Tension Test

A modified version of the rod tension test was used to determine the capacity of the slip joints. This test is illustrated in Fig. 6 and referred to as the slip joint test.
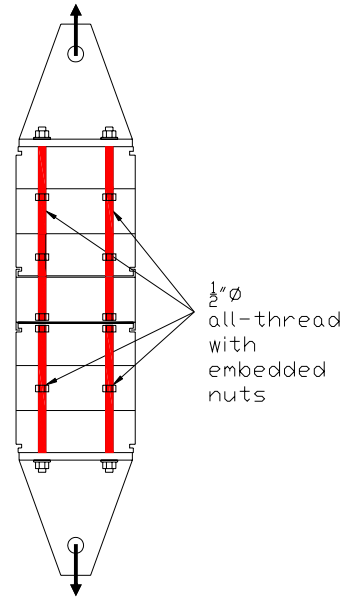

Figure 6: AFRL Slip Joint Test

The overall composite behavior test matrix is shown in Table 4. Results and observations are discussed separately for each type of test in the following paragraphs.

Wrench Tests – Results & Observations

The testing apparatus was designed to be very stiff in order to limit the induced vibration or bounce in recorded load data at higher stroke rates. A sample of the recorded test data for each stroke rate is shown in Fig. 7 for the 8" form. The first peak is the initial concrete crack followed by an immediate drop in load as the crack separates and all tension is transferred to the polymer tension area. At the two higher stroke rates small load oscillations occur in the next chart region as the PVC stress increases. These oscillations reflect the fundamental frequency of the test apparatus. They dampen out before the PVC reaches its max strength. A second peak occurs for the two slower rates which the video revealed was a second crack in the concrete. The load temporarily drops as the second crack separates and then the PVC reloads. At the 0.003 stroke rate the PVC had already reached maximum strength before the second concrete crack so the subsequently reloading of the PVC did not exceed the second data peak. This was not the case for the 0.167 stroke rate. The PVC reached its maximum strength after the second concrete crack. Multiple concrete cracks followed by rapid unloading and reloading of the PVC were also evident in the E72 test results conducted by others.

Slippage at the PVC - concrete interface was evident in the test videos, immediately after concrete cracking. As one might expect, the PVC tensile failures were significantly different from the slowest to highest stroke rates. PVC at the higher stroke rates exhibited behavior that could be described as shattering while failure at slower rates exhibited discoloring and stretching prior to rupture. Tensile stress waves immediately after first rupture are suspected as the cause for the shatter effect. Photographs of these contrasting failure types are illustrated in Fig. 8 (a) & (b).

8" Form Wrench Tests @ 0.003, 0.167 & 2 in./sec. Stroke Rates
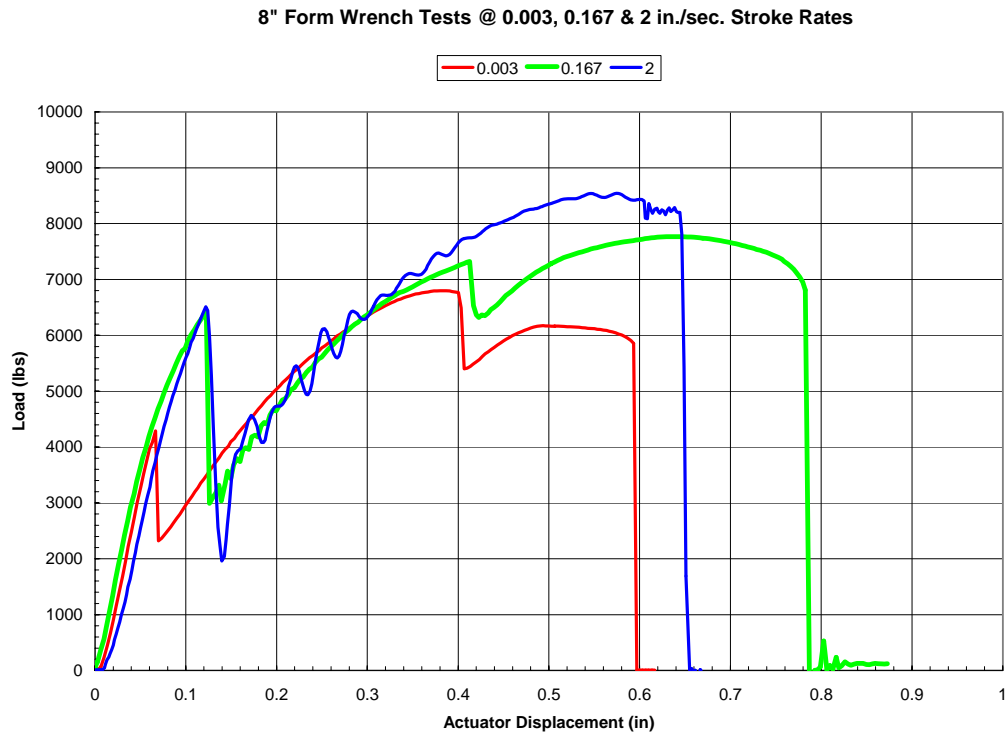

Figure 7: Sample Wrench Test Data (8" Form)

(a) Failure @ 0.003 in/sec Stroke Rate

(b) Failure @ 2 in./sec Stroke Rate

Figure 8: Wrench Test PVC Failures

A summary of the wrench test results is shown in Table 3. The approximate moment and elongation were calculated assuming straight line geometry for the apparatus top beam and ignoring the small amount of horizontal translation as the apparatus rotated. The percent increase in load as the stroke rate increases is very consistent between the components. For the non-insulated components the top beam connection is rigid so after concrete cracking the PVC tension area and compression block are the only significant forces opposing rotation. This is not the case for the 8" insulated component which has a 2" insulated PVC cavity on the compression side. How this affects the force

couple and moment transfer is uncertain but it has the most impact at the slower testing speeds. The moments were used for validation purposes in the Analysis section.

Table 3: Wrench Test Average Results

Component	Stroke Rate (in./sec)	Peak Load (lbs)	Load Increase (%)	Approximate Peak Moment (in.-kips)	Approximate Elongation @ Peak (in.)
4"	0.003	1,963		29.0	0.36
	0.167	2,303	17.3	33.8	0.45
	2	2,603	32.6	38.2	0.50
6"	0.003	3,653		50.1	0.34
	0.167	4,271	16.9	58.5	0.43
	2	4,904	34.2	67.0	0.52
8" Insulated	0.003	4,772		60.5	0.48
	0.167	5,943	24.5	75.2	0.62
	2	6,257	31.1	82.5	0.73
8"	0.003	6,526		82.5	0.40
	0.167	7,675	17.6	96.8	0.51
	2	8,586	31.6	108.2	0.61

Rod Tension Tests – Results & Observations

The expectation of the rod tension tests was that the recorded load data and forensics would provide more understanding about the PVC web response during crack separation. Evidence of vertical plane failure at the web-face intersection was observed in one test. It was not possible to determine conclusively whether the horizontal web tearing propagated from inside to outer face or outer face to inside based on the recorded data and video scrutiny. It is hypothesized that the tearing propagated from the outside to the inside. A great deal more slippage (length) between concrete and PVC tension face was evident in these tests compared to the wrench tests. Recorded data for 8" single rod tests at 0.167 in./sec stroke rate is shown in Fig. 9.
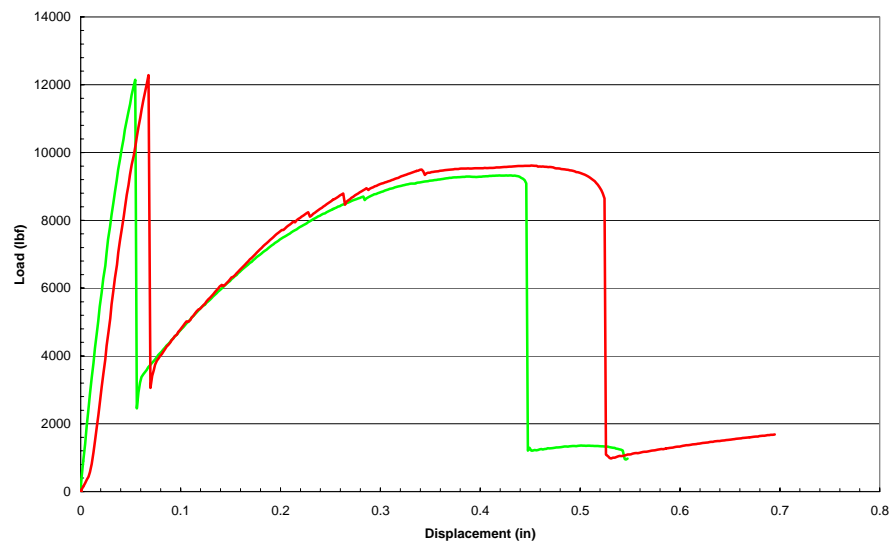
8" Form Single Rod Tension Tests

Figure 9: Single Rod Tension Test, 8" Form @ 0.167 in./sec Stroke Rate

Table 4: Composite Behavior Test Matrix

Panel Type	Test Type	Stroke Rate (in./sec.)	Repetitions
100 mm (4")	Wrench	0.003	3
		0.167	3
		2	3
	Single Rod Tension	0.167	2
		2	1
	Slip Joint	0.0167	2
		2	1
150 mm (6")	Wrench	0.003	1
		0.167	1
		2	1
	Single Rod Tension	0.167	2
		2	1
	Double Rod Tension	0.167	2
		2	1
	Slip Joint	0.0167	1
		2	1
200 mm (6" + 2" Insul.)	Wrench	0.003	1
		0.167	1
		2	1
	Single Rod Tension	0.167	2
		2	1
	Double Rod Tension	0.167	2
		2	1
	Slip Joint	0.0167	1
		2	1
200 mm (8")	Wrench	0.003	1
		0.167	1
		2	1
	Single Rod Tension	0.167	2
		2	1
	Double Rod Tension	0.167	2
		2	1
	Slip Joint	0.0167	1
		2	1

Fig. 9 has two peaks. The first correlates to concrete tension failure of the full sample cross section while the second reflects the maximum load carried by the PVC cross section before the highest tension face failed. Summary data for the single and double rod tension tests is shown in Tables 5 and 6 respectively.   Note that the concrete tension peak exceeds the PVC tension face peak for the 8" component.   The double rod tests had higher loads for both peaks due to a better balance of load carried by the two PVC faces.

Table 5: Single Rod Tension Test Summary

Component	Concrete Tension		PVC Tension		Max
	Load	Displ	Load	Displ	Load
4"	10,490	0.042	14,487	0.353	14,487
6"	10,733	0.050	11,604	0.547	12,271
8" Insulated	10,614	0.045	13,713	0.443	13,713
8"	13,776	0.068	9,914	0.411	13,776

Wt of testing apparatus and concrete sample included

Table 6: Double Rod Tension Test Summary

Component	Concrete Tension		PVC Tension		Max
	Load	Displ	Load	Displ	Load
6"	15,155	0.049	14,746	0.342	15,465
8" Insulated	16,274	0.052	17,096	0.359	17,438
8"	17,353	0.052	14,209	0.420	17,353

Wt of testing apparatus and concrete sample included

Slip Joint Tests – Results & Observations

Slip joint test results are shown in Table 7. Note the smaller increase in capacity as the stroke rate increased.

Table 7: Slip Joint Test Summary

Stroke Rate (in./sec)	Maximum Load			
	4"	6"	8" Insul.	8"
0.0167	2,496	2,234	9,531	Failed
2	4,741	3,707	14,241	16,019

Wt of testing apparatus and concrete sample included

EXPLOSIVE EXPERIMENTS

Full-scale wall experiments were conducted to validate and refine analytical models and add to the overall composite behavior understanding. A total of six walls using the various PVC form components were included in three separate detonations. The experiments are summarized in Table 8.

Table 8: Explosive Experiment Summary

ID Fig.	Wall Description	Prediction	Results & Observations
1 Figure 15	8" Form, 12' vertical span, dowelled into concrete at the base and a pin restraint at the top.	No Collapse 5+ in. deflection	• Resisted the blast with no damage or residual deflection, peak inward deflection of 2.8". • 42 psi reflected pressure, 226 psi-msec impulse. • (See forensic bladder test for more discussion)
	6" + 2" insulation Form, 12' vertical span, dowelled into concrete at the base and a pin restraint at the top	Possible Collapse 8+ in. deflection	• Resisted the blast with no damage or residual deflection, peak inward deflection of 4.7". • 43 psi reflected pressure, 228 psi-msec impulse. • (See forensic bladder test for more discussion)
2 Figure 16	4" Form, 9' vertical span, dowelled into concrete at the base and a pin restraint at the top.	Collapse	• Tension failure in PVC at mid-height /11.2" defection, wall collapsed. • 66 psi reflected pressure, 378 psi-msec impulse.
	6" Form, 9' vertical span, dowelled into concrete at the base and a pin restraint at the top.	Likely Collapse 12+ in. deflection	• Tension failure in PVC at mid-height/6.4" defection, wall did not collapse, peak inward deflection of 9.3". • 65 psi reflected pressure, 386 psi-msec impulse.
	4" Form, 9' vertical span, dowelled into concrete at bottom and top as retrofit behind unreinforced 8" CMU wall.	No Collapse 6+ in. deflection	• Resisted the blast with no damage or residual deflection, peak inward deflection of 5.1" • 59 psi reflected pressure, 317 psi-msec impulse.
3 Figure 17	8" Form, filled with sand/gravel mix only, 12' vertical span, pin restraint at bottom and top.	No Collapse 7+ in. deflection	• Resisted the blast with no damage or residual deflection, peak inward deflection of 6.1". • 40 psi reflected pressure, 193 psi-msec impulse.

The purpose of the sand/gravel-filled wall experiment was to get a feel for how much of the peak wall response was due to mass effect versus the increased structural resistance provided by the uncracked concrete and subsequent composite PVC-cracked concrete resistance. The sand/gravel mixture was 10 pcf (7.2%) lighter than the concrete used in the 8" form wall in experiment 1. How much of the additional 1.4 in. of deflection was due to weaker resistance and/or a lighter wall is left up to the judgment of the individual. It is difficult to reach a consensus on the percentage of total deflection attributed to mass effect or resistance, however given the choice between mass and resistance, it is safer to choose mass.

Forensic Bladder Test

The first two walls (experiment 1) were closely examined after removal from the reaction structure to gain first hand knowledge about the extent of concrete cracking. AFRL designed a unique but simple method to accomplish this investigation; it is referred to as the forensic bladder test and is illustrated in Fig. 9. After the wall panel was positioned, full length strips of PVC were removed for the edge and center regions to reveal the underlying concrete. Visible cracks were marked prior to inflating the water bladder to flex the wall upward. Cracks only visible after

flexing were also marked. To mark these cracks and to take pictures, flexing of the walls was held at an upward deflection equal to the value measured during the actual blast response. The 8" form wall was flexed until the PVC ruptured in tension at just over 5 inches of deflection. A crack map of the 8" insulated form wall is shown in Fig. 10. Cracks are most frequent in the mid-height region but spread out over the center two thirds of wall height. As the wrench tests demonstrated, each crack represents load redistribution (i.e. energy absorption) which spreads the overall wall elongation over a higher total length of PVC. The greatest crack growth and PVC strain/rupture ultimately occurs at mid-height as predicted and verified in full-scale experiments.
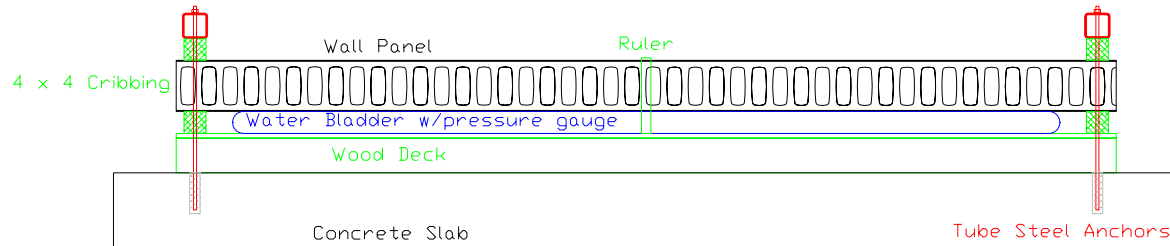
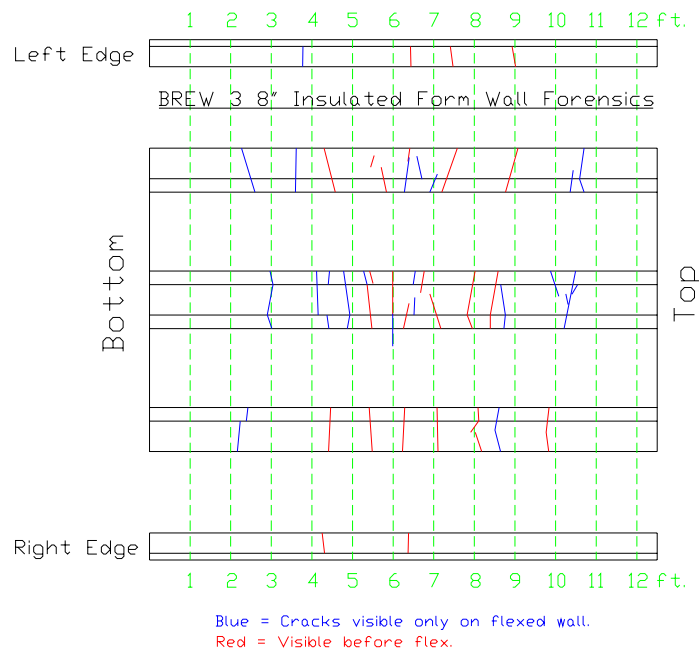Figure 9: Bladder Test Configuration

Figure 10: Bladder Test 8" Insulated Form Crack Map

ANALYSIS

Analyzing a concrete wall subjected to blast pressures is a complex problem. With simplifying assumptions it is still difficult to develop structural models that deliver repeatable precision when compared to full-scale experiments. PVC forms simplify wall construction but they add to the difficulty involved in developing analysis models. This being said, analysis models are an important deliverable for any blast research effort. AFRL has developed single degree of freedom (SDOF) and finite element models for stay-in-place PVC formed, unreinforced concrete walls. The detailed development of the SDOF resistance functions is slated for another paper and therefore not included in this paper. A general discussion of resistance function factors is discussed as background for the first generation resistance functions shown in Fig. 12.

There are many good references3 and adequate tools available for executing a SDOF analysis. The wall analysis code (WAC)4 developed and distributed by the U.S. Army Corp of Engineers was used as the analysis tool for this effort. The three basic elements in a SDOF analysis are as follows:

1. Loading function – Blast pressure vs. time data.
2. Wall mass function – Uniform for full wall height and time simplifies the model.
3. Resistance function – Force/Moment vs. deflection data. In the case of blast analysis, moment is usually converted to an equivalent uniform pressure for the full wall height.

The first two are straight forward, so the lion share of the effort is spent on developing resistance functions based on the information available. A generic resistance function for a concrete wall is shown in Fig. 11.

R_e = peak uncracked resistance (moment capacity)
R_u = ultimate strength resistance (moment capacity)
y_e = deflection at uncracked resistance
Y_p = deflection at ultimate resistance
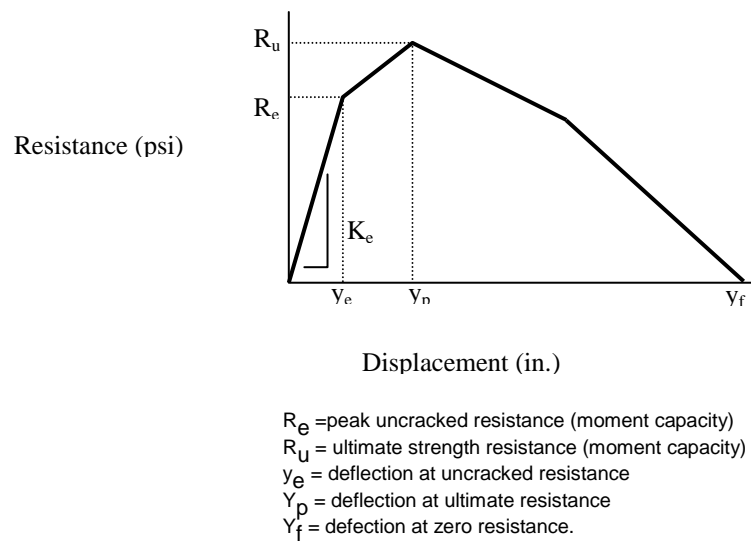Y_f = defection at zero resistance.

Figure 11: Generic Concrete Wall Resistance Function

The portion of the resistance curve beyond the peak uncracked resistance is heavily dependent on assumptions for the PVC stress-strain relationship. To complicate matters, as the wall deflects multiple concrete cracks occur and expand which in turn unloads and reloads PVC on the tension face and may alter the strain rates at crack locations. The bottom line is that PVC strain rate during blast response is extremely difficult to verify and a function of wall deflection, the deflected shape and the length of PVC being strained. PVC length is in turn a function of the number of cracks in the encased concrete that are expanding during the blast response. Table 9 illustrates how deflection (., deflected shape (parabola) and involved or elongated length assumptions impact strain.

Table 9: Range of Strains for 9 ft. High Wall

Defl(δ)	Parabolic Shape Elongation	Assumed Length Being Elongated				
		20% Height	10% Height	3"	1"	0.5"
1	0.02	0.1%	0.2%	0.8%	2.5%	4.9%
2	0.10	0.5%	0.9%	3.3%	9.9%	19.7%
3	0.22	1.0%	2.1%	7.4%	22.2%	44.4%
4	0.39	1.8%	3.6%	13.1%	39.4%	78.8%
5	0.61	2.8%	5.7%	20.5%	61.4%	122.8%
6	0.88	4.1%	8.2%	29.4%	88.2%	176.5%
6.4	1.00	4.6%	9.3%	33.4%	100.3%	200.6%
7	1.20	5.5%	11.1%	39.9%	119.8%	239.6%
8	1.56	7.2%	14.4%	52.0%	156.0%	312.0%
9	1.97	9.1%	18.2%	65.6%	196.8%	393.6%
10	2.42	11.2%	22.4%	80.7%	242.1%	484.1%
11	2.92	13.5%	27.0%	97.2%	291.7%	583.5%
11.2	3.02	14.0%	28.0%	100.7%	302.2%	604.4%
12	3.46	16.0%	32.0%	115.2%	345.7%	691.4%

The 6" wall in experiment 2 had PVC tensile failure at a deflection of 6.4 in., occurring at 61 msec. The 4" wall in the same experiment had PVC tensile failure at a deflection of 11.2 in., occurring at 60 msec. From Table 6 these two data points would correlate to 1 in. and 3 in. of total elongation if the parabolic shape assumption is valid; which it appeared to be in the video footage. It is not possible to know how much of that elongation took place exactly where the PVC failed so assumptions are required. The testing and experiments provide data to hopefully improve the validity of these assumptions.

Resistance Functions

The first generation SDOF resistance functions corresponding to the wall experiments conducted thus far are shown in Fig. 12. As the predicted versus actual deflection data in Table 8 indicate, these resistance functions yield predictions which are too conservative for practical use. Fig. 13 shows this conservatism as predicted versus actual deflection for the 8" wall of experiment 1.
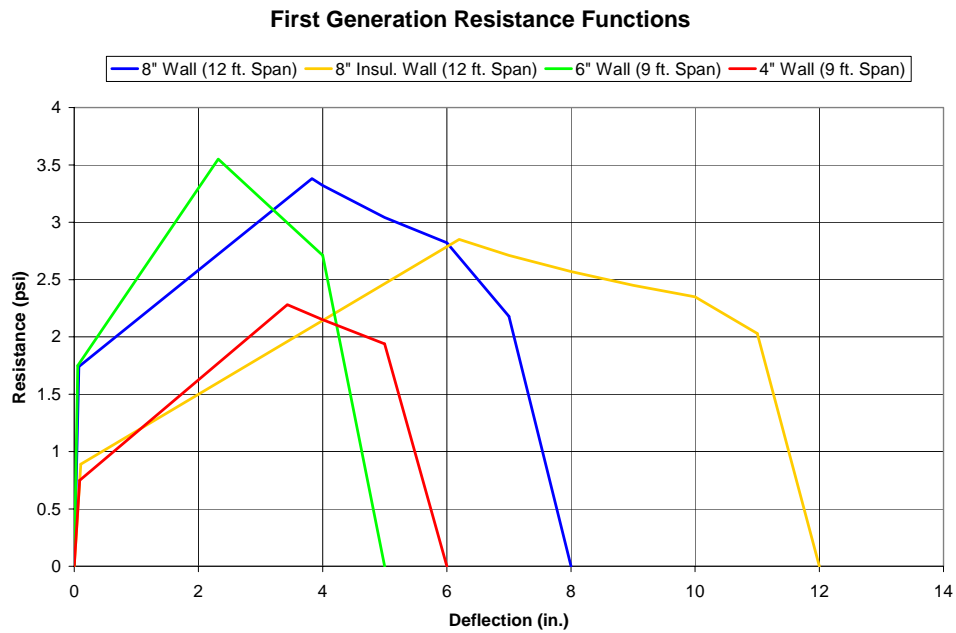
First Generation Resistance Functions

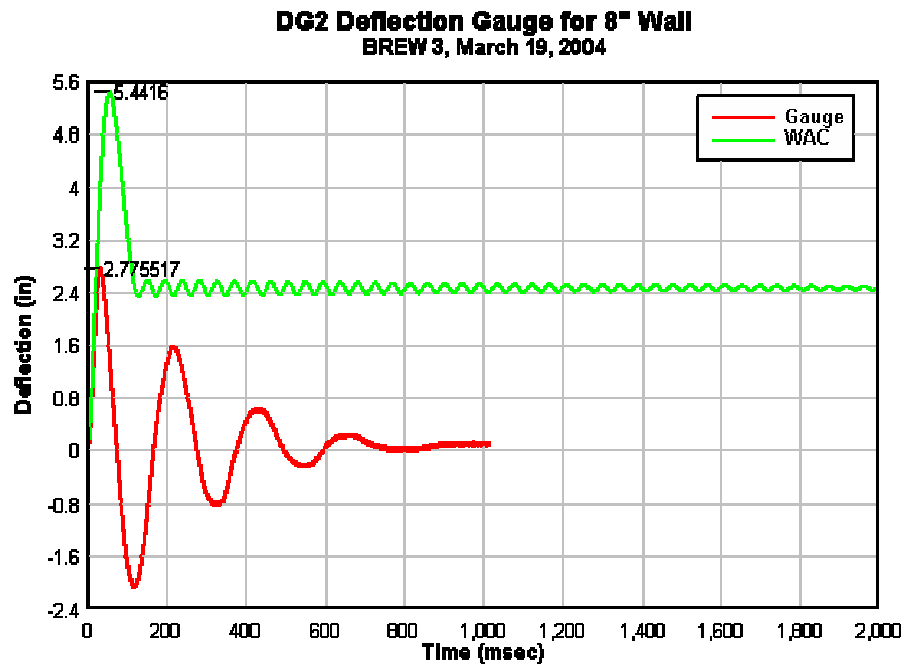Figure 12: First Generation Resistance Functions

Figure 13: Experiment 1 – 8" Wall 1ˢᵗ Generation Deflection Comparison

AFRL uses LS-DYNA as the finite element (FE) model software. The following bullets describe the first generation FE models in a succinct manner:

1. PVC modeled as shell elements.
2. Concrete and insulation modeled as 8-node solid elements.
3. Insulation given essentially zero stiffness and strength.
4. PVC face to concrete contact surface allowed to slip.
5. PVC web to concrete contact surface not allowed to slip.
6. Corings through webs not modeled (i.e. concrete not horizontally continuous through webs)
7. Concrete constitutive material model = MAT_BRITTLE_DAMAGE
8. PVC constitutive material model = MAT_PLASTICITY_WITH_DAMAGE
9. 5% critical damping

A good comparison of deflection versus time is shown in Fig. 14 for the 8" wall of experiment 1. AFRL, through the University of Alabama, Birmingham, will continue to improve the model. Getting the PVC material model to exhibit the desired rupture behavior at max tensile strength is one area that will be refined along with a continuous search for better concrete constitutive material models.
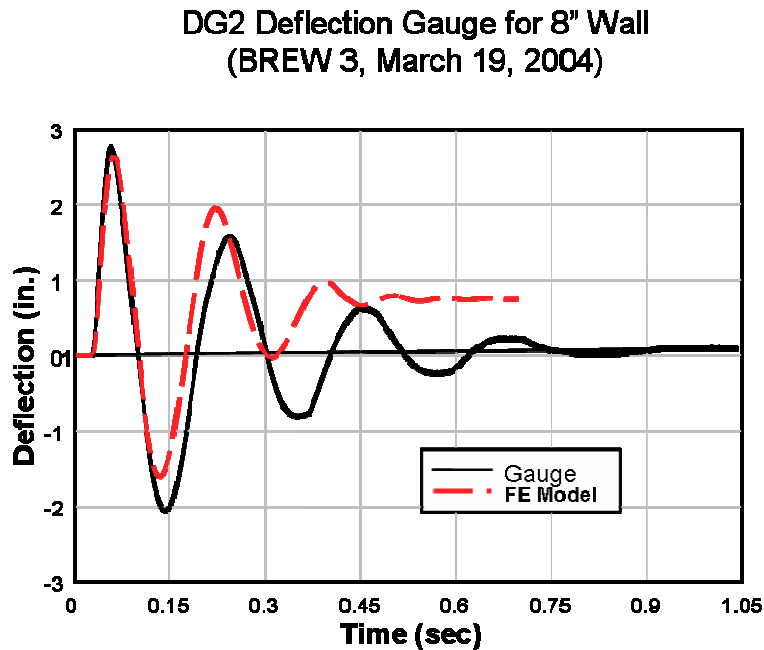

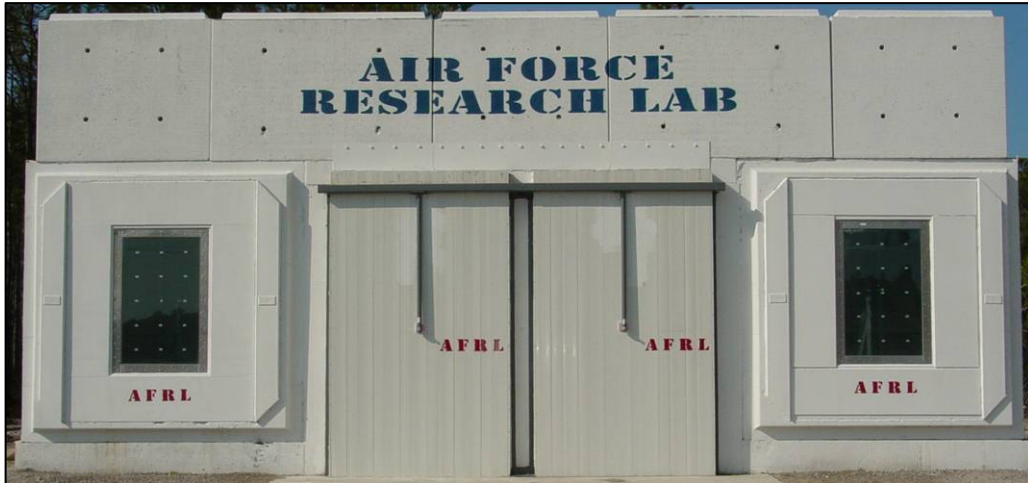Figure 14: Experiment 1 – 8" Wall 1$^{\underline{st}}$ Generation FE Deflection Comparison

Figure 15: Experiment 1 Pre-Detonation (8" & 8" Insulated)

Figure 16: Experiment 2 Pre-Detonation (4", 6" & 4" Behind CMU)

Figure 17: Experiment 3 Post-Detonation (8" Form Sand/Gravel Filled)

CONCLUSIONS

Stay-in-place PVC forms add significant blast protection for a concrete wall through composite strength behavior with the concrete and several advantageous characteristics inherent to PVC. The material characteristics with the greatest contribution are:

1. Significant increase in maximum strength as strain rate increases.
2. Strain at maximum strength is an order of magnitude higher that reinforcing steel.

These two attributes combine to allow considerable wall deflection and still have significant strength and stored energy to rebound the wall back to vertical. PVC encasement also has the advantage of capturing most wall fragments even when the wall fails.

Single degree of freedom dynamic analysis is a viable method to predict wall response for walls constructed with stay-in-place PVC forms.

RECOMMENDATIONS AND FUTURE RESEARCH

Design engineers should consider the blast protection advantages of stay-in-place PVC forms in wall construction decisions. The research knowledge on walls without rebar is transferable to walls with rebar.

AFRL will finish the development of second generation SDOF resistance models taking full advantage of multiple crack locations and PVC strain rate effects. The next research phase will extend the knowledge learned in this phase to rebar reinforced walls with and without openings holding advanced AFRL blast windows. Strain compatibility between the rebar and PVC during blast response is anticipated as an important element for the next research phase. Future full-scale experiments will consider physical and video methods to capture deflection at multiple wall heights to validate deflection shape assumptions.

AFRL has conducted full-scale experiments that included PVC form configurations filled with only soil and concrete in combination with soil filled cavities. Both configurations performed well and have spun off into an additional area of research for PVC concrete form systems; PVC forms as expeditionary or permanent blast, ballistic and vehicle barriers.

ACKNOWLEDGEMENTS

Note: AFRL does not endorse products used for research.

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